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Development of a mobile pulse waveform analyzer for cardiovascular health monitoring

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Abstract

Noninvasive pulse waveforms contain rich pathophysiological information of cardiovascular system. It is hereby a tradition of interest to implement risk stratification by pulse waveform monitoring and analysis. In contrast to conventional computer- or network-based solutions, we attempt to accomplish pulse waveform monitoring and analysis within a self-contained mobile platform. It adopts a compact biosensor for pulse waveform acquisition. The collected signals are then submitted to a core board for pulse waveform processing and analysis. In addition, the core board coordinates user interaction and network communication too. Such compact pulse waveform analyzer is of great help for cardiovascular health monitoring at home. A carefully designed evaluation has been undertaken within our research group. The results confirmed its prospect in home healthcare.

Keywords: Cardiovascular health monitoring; Embedded system; Home healthcare; Pulse waveform analysis

1. Introduction

E-home healthcare provides an alternative solution to the existing paradigms of healthcare delivery. Among various proposals, those based on self-serviced health monitoring receive widespread investigation. In essence, such type of paradigms are built on smart biosensor networks, namely, distributing various biosensors to individual home for health monitoring whilst networking those biosensors to health centers for medical evaluation. Then, based on the long-term health recordings, it is possible to tell home subjects a few valuable health clues, for example, the threat of a specific disease or the trend of health status [1].

In view of the prevalence of cardiovascular diseases, the relevant physiological signals receive much attention in home health monitoring, especially electrocardiogram (ECG) and arterial blood pressure (ABP). ECG has been well investigated to monitor the transient myocardial activities. And a plethora of solutions have been proposed for cardiovascular health monitoring based on ECG [2–4]. Nevertheless, ECG is good at cardiac function monitoring but not vascular alterations. For instance, the P wave, the QRS complex and the T wave in each beat of ECG reflect the processes of myocardial polarization and depolarization only. During myocardial relaxation, ECG will not characterize blood circulation in cardiovascular system any more. However, a complete cardiovascular circulation consists of different stages in not only the heart but also the vasculature. Hence, as a complementary technology, blood pressure and pulse waveforms collected at peripheral arteries can serve to better risk stratification of cardiovascular system [5,6].

Kinetic blood circulation brings rich pathophysiological information of cardiovascular system. For instance, ABP has been long accepted as an effective risk factor of cardiovascular system. However, it is noteworthy that blood pressure monitoring only reflects several extreme, or average, values of kinetic blood circulation. Thus, compared with other advanced technologies such as ECG, blood pressure monitoring loses its

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capability to reflect the kinetic aspect of blood circulation, which is more valuable for health prognosis [5–7]. It is hereby a natural choice to record peripheral pulse waveforms, and find out more underlying risk factors.

As a matter of fact, pulse waveform monitoring and analysis owns a long tradition in both Oriental and Western Medicine [8,9]. And its mechanisms in risk stratification of cardiovascular system have been well investigated from different points of view. Now it is possible to derive a series of critical risk factors, such as cardiac output (CO), stroke volume (SV), systematic arterial compliance (SAC) and total peripheral resistance (TPR), from noninvasive pulse waveforms [7,8,10–12]. Moreover, a few commercial solutions have attempted to take advantage of noninvasive pulse waveform analysis for cardiovascular health monitoring [12–15]. But most of them are dependent on either personal computers [14] or central servers [15]. For convincing risk stratification, home subjects have to rely on their personal computers or effective network connection. With concerns on maneuverability, such modes of operational procedure definitely impair their popularity in home healthcare.

To resolve above challenges, our group has designed a self-contained pulse waveform analyzer by virtue of embedded systems and pervasive computing [1]. In a nutshell, it is aimed to accomplish the whole procedure of cardiovascular health monitoring within a mobile platform only. We paid special attention in this paper on those essential criteria determining the success of a health monitoring system, namely, good maneuverability, friendly interaction, easy interpretation and cost-effectiveness. The left sections were organized as follows: the underlying mechanisms of noninvasive pulse waveform monitoring and analysis were carefully examined in the next section; Section 3 was concerned with system design and technical development of the mobile pulse waveform analyzer; the prototyping pulse waveform analyzer has been prospectively validated within our research group, which was detailed in Section 4; the final section was for discussion and conclusion.

2. Pulse waveform monitoring and analysis

2.1. Pulse waveform monitoring

A biosensor competent for kinetic blood circulation takes a critical role in building the pulse waveform monitoring and analysis system. In fact, it is a long tradition of interest in clinical practice to master the genuine condition of blood circulation. Many invasive or mini-invasive technologies, such as angiocardiography and thermodilation, have been developed for that purpose. But those professional technologies are obviously not suitable for the routine practice of home healthcare. Similarly, with concerns on maneuverability and cost-effectiveness, the technologies of magnetic resonance and Doppler ultrasound, despite their popularity in clinical practice, have to be excluded in home health monitoring. Till now, merely applanation tonometry [16,17] and plethysmography [18] are popular for noninvasive pulse waveform monitoring.

Applanation tonometry has been widely recommended for radial arterial pulse waveform characterization. Theoretically speaking, in applanation tonometry, a high-fidelity tonometer is firstly placed on the accessible arteries with gentle pressure so as to occlude dynamic blood flow partially. Then, blood pulsation through that site will be captured and converted to other types of electrical signals. Previous studies have confirmed such pulse waveforms are accurate and comparative to those obtained invasively by intra-arterial measurements [19]. Similarly, due to vascular elasticity, there will be a tiny discrepancy of tissue volume as dynamic blood flow passes through it. Plethysmography is right to record such volume variation in a graphic manner. If mapped with optic reflection, the plethysmography is often termed as photoplethysmography. Due to vascular cushion and tissue diffusion, the collected plethysmograms reflect a rough profile of pulse waveforms only. But they are indeed able to provide considerable underlying characteristics of blood circulation [20]. Fig. 1 illustrates a segment of invasive pulse waveforms (CMS, Philips®, Netherlands) versus two segments of noninvasive ones (Finometer, Finapres®, Netherlands and HK-2000C, Huake®, China).

2.2. Pulse waveform analysis

Pulse waveforms reflect the kinetic aspect of blood circulation. So their morphology and rhythm are essentially determined by the pathophysiological condition of cardiovascular system, such as cardiac function and vascular elasticity. In the first, within each systole, the left ventricle ejects the refreshed blood to aorta, and then arteries. The energy will be partially preserved by elastic vasculature so as to sustain blood circulation during cardiac diastole, and partially consumed by blood propagation. Meanwhile, the impedance mismatch makes partial arterial blood flow travel backward, which exerts constructive or destructive effect on blood circulation [21]. At last, autonomic nervous system regularizes the whole procedure and balances the blood in arterial and venous circulations. Hence, the pulse waveform collected at any site should be attributed to the integrated effects of cardiac pulsation, vascular elasticity and pulse wave reflection [9,21]. Fig. 2 illustrates how kinetic blood flow and pulse wave reflection synthesize the final pulse waveform.

It has been a long tradition of interest to derive out critical risk factors from pulse waveforms [7,8,10–12]. Among various proposals, those methods based on lumped parametric models are widely accepted in both academic and industrial solutions (Fig. 3). For instance, such types of parametric models have been utilized to simulate human arterial system under variable pathophysiological conditions [22,23]. Moreover, Finometer® (Finapres, Netherlands) takes advantage of a 3-element parametric model to derive out the risk factors including CO, SV, SAC, and TPR, etc. [24].

In essence, lumped parametric models attempt to characterize the distributed properties of cardiovascular system by a limited number of discrete components with specific physical meaning but neglecting their spatial distribution. Such type of models are contributive to the introduction of electrical analog

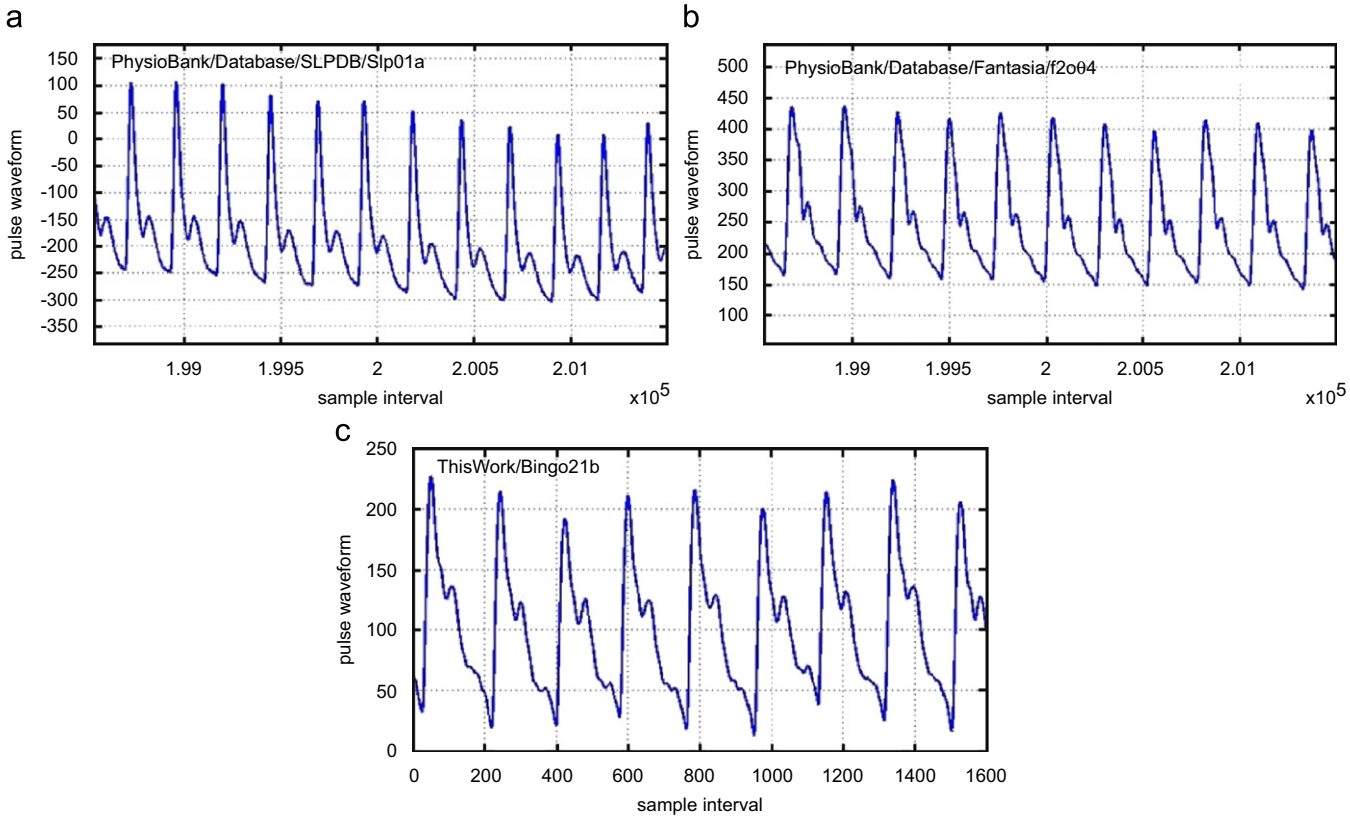

Fig. 1. Pulse waveform monitoring (*a*: Invasive; *b*: Plethysmography; *c*: Applanation Tonometry).

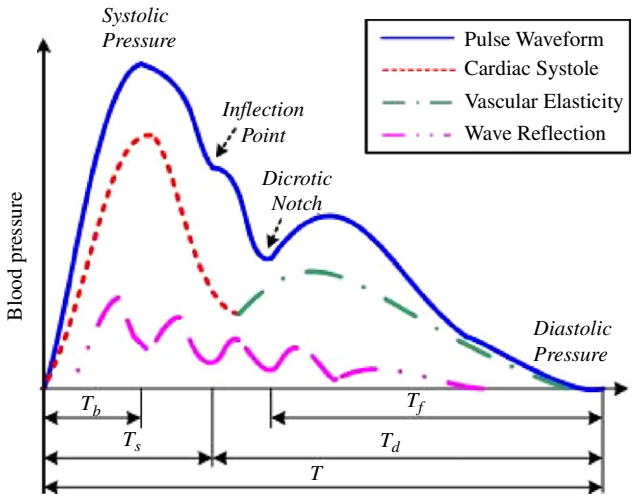

Fig. 2. A synthesized pulse waveform.

systems composed of resistances as the electrical equivalent of hydraulic resistance (friction in the small arterioles and capillaries) and capacitances as arterial compliance (buffering capacity of the large elastic arteries). Then many analytical methods in electrical models turn applicable to blood circulation in cardiovascular system [22,23,25]. And a few mathematical formulas, as shown in (1)–(5), have been derived out to characterize lumped parametric models [1,8,26].

$$\mathrm{CO} = K \cdot \frac{\int_T p(t)\,\mathrm{d}t}{\mathrm{TPR}}, \tag{1}$$

$$\mathrm{SV} = \frac{\mathrm{CO}}{\mathrm{HR}}, \tag{2}$$

$$\mathrm{TPR} = \frac{\mathrm{MAP}}{\mathrm{CO}}, \tag{3}$$

$$\mathrm{SAC} = \frac{\int_{T_d} p(t)\,\mathrm{d}t}{\int_{T_s} p(t)\,\mathrm{d}t + \int_{T_d} p(t)\,\mathrm{d}t} \cdot \frac{\mathrm{SV}}{P_I - P_D}, \tag{4}$$

$$\mathrm{PAWP} = \mathrm{LAP} = K \cdot \frac{T_b}{T_f}, \tag{5}$$

where $p(t)$ means pulse waveform contour; T_s, T_d, T_b and T_f are the intervals as shown in Fig. 2; P_D and P_I are diastolic blood pressure and the blood pressure at inflection point respectively; K is a coefficient dependent on the subject's demographic indices, such as age, gender, weight, and height. Finally, HR stands for heart rate, MAP for mean arterial pressure, PAWP for pulmonary arterial wedge pressure, and LAP for left atrial pressure. Thus, with delineated pulse waveforms, it is possible to derive out a series of quantitative risk factors for cardiovascular health monitoring.

3. Mobile pulse waveform analyzer

Currently, there have been many off-the-shelf biosensors candidate for pulse waveform monitoring [24,27]. They are powerful enough to accomplish pulse waveform acquisition, filtering, and amplification within a compact platform. So, for a mobile pulse waveform analyzer, it is aimed to implement the

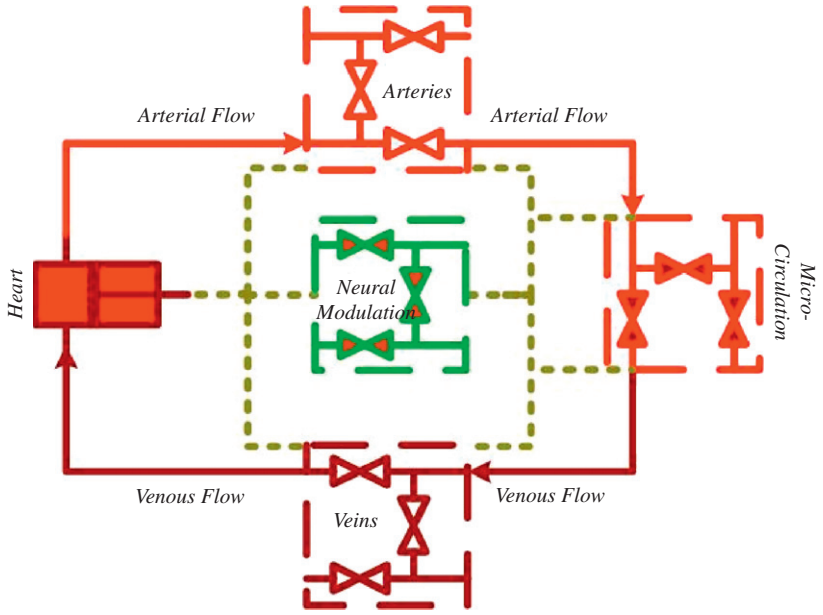

Fig. 3. Lumped parametric model of cardiovascular circulation.

subsequent pulse waveform analysis, including delineation, calculation and health prognosis, within an embedded platform too. In Ref. [1], a modular pulse waveform analyzer has been proposed for cardiovascular health monitoring. It firstly takes advantage of an applanation tonometer for pulse waveform acquisition. The collected pulse waveforms are then submitted to a mobile platform for processing and analysis. A touch screen is responsible for user interaction including data input, command prompt and information feedback. Finally, it also equips a network module for data synchronization and medical support.

The overall development of that mobile pulse waveform analyzer was based on a hierarchical embedded platform (HHARM2410, HHTech®, China). There is a core board composed of an ARM920T processor (S3C2410, Samsung®, Korea), 64M 32-bit SDRAM, and 16M 16-bit Flash (Fig. 4a). It coordinates the whole operational procedure, and keeps all data as well as programs. On the other hand, the core board controls the integrated TFT LCD and touch screen (LQ035Q7DB02, Sharp®, Japan) via a GPIO (General Purpose I/O) interface (Fig. 4b). Other than user interaction, there are essential ports for network communication and pulse waveform acquisition (HK2000C, Huake®, China) (Fig. 4d) in the extended board (Fig. 4c). Software development was based on the ARM Linux with a series of open modules, such as MiniGUI (Feynman®, China). All modules were programmed in C Language, including those for pulse waveform analysis, user interaction, and network communication.

Maneuverability takes a first place throughout the development of that mobile pulse waveform analyzer. Its overall operational procedure follows the flowchart in Fig. 5. To initiate health monitoring, the analyzer firstly reminds the subject to wear applanation tonometer in its welcome screen (Fig. 5a). Then, it requests the subject to input his/her demographic indices via its touch screen (Fig. 5b). During the procedure of

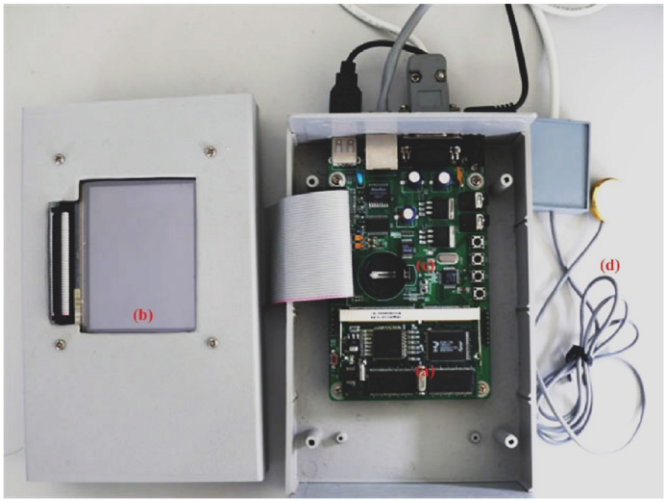

Fig. 4. Prototyping mobile pulse waveform analyzer.

pulse waveform monitoring (Fig. 5c), the analyzer tries its best to adjust the applanation tonometer for optimal pulse waveforms. Finally, based on the derived risk factors, the analyzer executes an embedded medical advisory system for health prognosis [1].

The mobile pulse waveform analyzer is able to report hierarchical health clues. In the first screen (Fig. 5d), it illustrates the collected pulse waveforms with fiducial points, as well as a series of quantitative risk factors. Moreover, in the bottom of that screen, the analyzer tells home subject the risk of cardiovascular system with a remarkable indicator: red for exacerbation, yellow for noteworthiness, and green for fair health. In the case of red indicator, the subject is advised to visit health centers for professional examination. In some occasional cases, the analyzer will report a white indicator, which means the insufficiency of embedded medical advisory system. It is hereby

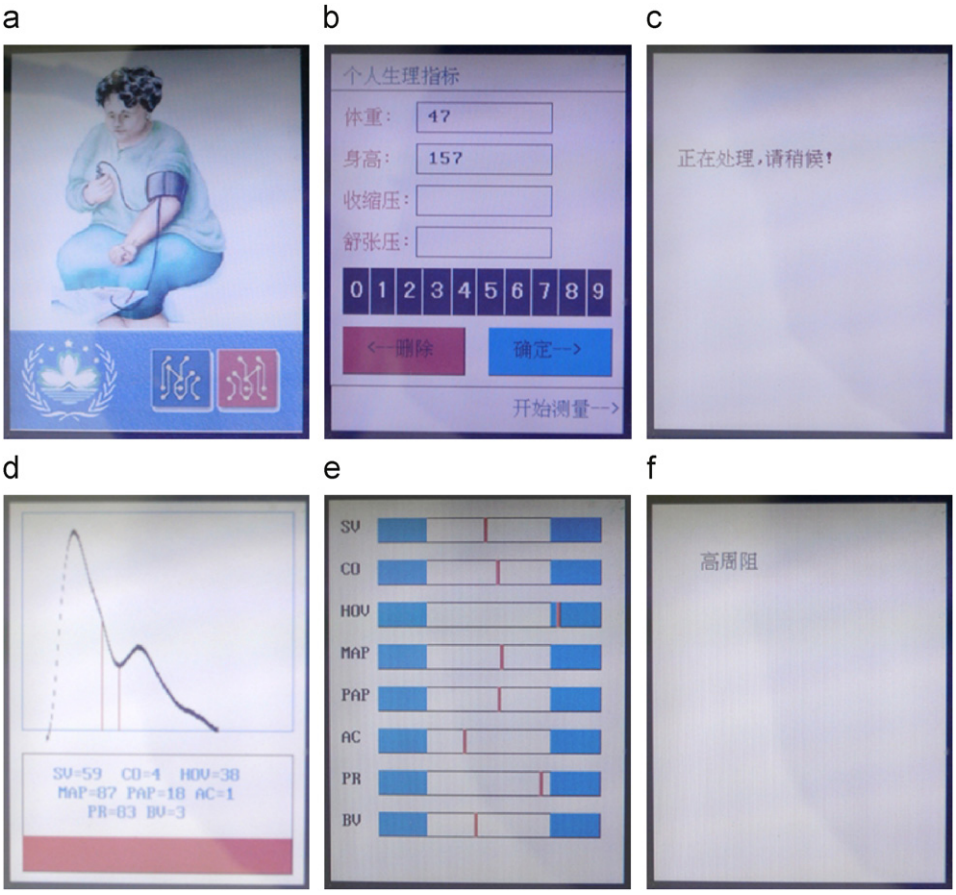

Fig. 5. Software flowchart of pulse waveform analyzer.

Table 1
Personal information of the participants

Subject	Gender	Age	Height (cm)	Weight (kg)	CVD[a]
aries001	Female	25	157	48	No
bingo001	Male	28	166	67	No
charley001	Male	59	177	85	Yes[b]
vince001	Male	26	166	65	No

[a]CVD: Cardiovascular diseases.
[b]Confirmed premature ventricular contraction.

necessary to link the mobile pulse waveform analyzer to central servers for case report and system upgrading. Then, in the second screen (Fig. 5e), the analyzer illustrates various risk factors and their relations to respective risk intervals. Finally, if the subject seeks for more information, the embedded medical advisory system will attempt to report health prognosis and relevant advices in the third screen (Fig. 5f).

4. Evaluation

4.1. Methods

Our research group has undertaken a prospective validation of the prototyping pulse waveform analyzer. Four members of our research group were involved in a 7-day validation procedure (Table 1).

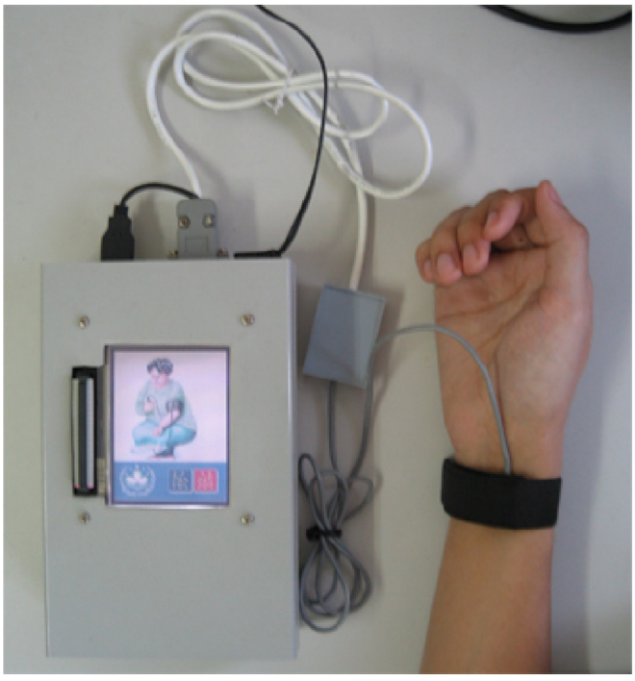

Fig. 6. Cardiovascular health monitoring with mobile pulse waveform analyzer.

A commodious room with good ventilation and illumination was reserved for the overall evaluation. The participants visited for cardiovascular health monitoring three times a day at 9:00

Table 2
Results of 7-day prospective validation

Subject	Time	Blood pressure		SV		CO		SAC		TPR	
		SBP	DBP	REF	Test	REF	Test	REF	Test	REF	Test
aries001	9:00	105	67	66.7	64.8 ± 4.0	4.0–6.7	5.8 ± 0.5	> = 1.2	1.2 ± 0.1	800–1300	1185.7 ± 98.7
	14:00	101	64		66.6 ± 5.1		6.1 ± 0.8		1.3 ± 0.1		1095.7 ± 112.7
	18:00	101	68		61.8 ± 4.4		5.4 ± 0.3		1.3 ± 0.1		1259.1 ± 71.8
bingo001	9:00	118	72	90.5	108.4 ± 13.8	5.4–9.1	7.3 ± 0.7	> = 1.2	1.4 ± 0.2	800–1300	1055.6 ± 86.5
	14:00	118	68		118.0 ± 20.7		7.5 ± 0.5		1.4 ± 0.2		1013.1 ± 102.9
	18:00	121	81		107.0 ± 8.6		6.4 ± 0.5		1.6 ± 0.1		1285.2 ± 87.0
charley001	9:00	120	70	120.9	142.4 ± 15.8	7.3–12.1	9.9 ± 1.2	> = 1.2	1.4 ± 0.2	800–1300	775.1 ± 76.1
	14:00	120	70		121.1 ± 11.8		8.9 ± 0.6		1.2 ± 0.1		834.7 ± 44.9
	18:00	120	70		138.6 ± 19.7		9.3 ± 1.7		1.4 ± 0.2		855.4 ± 188.8
vince001	9:00	123	78	92.8	94.6 ± 23.8	5.6–9.3	7.4 ± 2.0	> = 1.2	1.2 ± 0.3	800–1300	1104.9 ± 296.3
	14:00	120	79		96.5 ± 7.2		7.7 ± 0.7		1.1 ± 0.1		954.1 ± 83.4
	18:00	126	85		96.8 ± 6.8		7.4 ± 0.8		1.4 ± 0.3		1105.7 ± 95.6

		HOV		PAP		BV		Conclusion[a]
		REF	Test	REF	Test	REF	Test	
aries001	9:00	21.2–39.6	39.9 ± 3.7	15–30	22.0 ± 5.8	3.6	3.8 ± 0.1	Insufficient myocardial blood supply
	14:00		38.4 ± 2.0		22.5 ± 2.1		4.0 ± 0.1	Insufficient myocardial blood supply
	18:00		35.4 ± 2.2		17.2 ± 2.6		3.7 ± 0.1	Normal cardiovascular system
bingo001	9:00	25.3–47.2	36.0 ± 6.5	15–30	14.4 ± 2.2	4.9	5.1 ± 0.1	Normal cardiovascular system
	14:00		32.8 ± 6.4		14.7 ± 1.9		5.3 ± 0.1	Over stroke volume
	18:00		36.3 ± 7.7		10.7 ± 3.5		4.7 ± 0.1	Compensatory stroke power
charley001	9:00	30.1–56.2	44.4 ± 1.1	15–30	16.1 ± 2.3	6.4	6.5 ± 0.1	Normal cardiovascular system
	14:00		39.7 ± 1.5		19.2 ± 2.5		6.3 ± 0.1	Normal cardiovascular system
	18:00		44.1 ± 7.8		20.4 ± 4.0		6.4 ± 0.1	Over stroke volume; compensatory stroke power
vince001	9:00	25.3–47.2	44.6 ± 7.9	15–30	25.4 ± 21.0	4.9	4.8 ± 0.4	Normal cardiovascular system
	14:00		36.6 ± 6.1		19.1 ± 4.1		5.1 ± 0.1	Normal cardiovascular system
	18:00		38.3 ± 4.7		12.2 ± 2.4		4.6 ± 0.1	Compensatory stroke power

[a]Reported by the embedded medical advisory system.

AM, 14:00 PM and 18:00 PM, respectively. Before each time of monitoring, it was mandatory for the participants to have a rest (5 min) at first. Then a technician assisted them for blood pressure monitoring with a wrist sphygmomanometer and a mercury one. Their average values were taken as the blood pressures for pulse waveform calibration, including systolic blood pressure (SBP) and diastolic blood pressure (DBP). Finally, the prototyping pulse waveform analyzer was taken advantage for cardiovascular health monitoring as shown in Fig. 6.

4.2. Results

The prototyping pulse waveform analyzer may derive over 20 hypothetic risk factors. Some of them have been evaluated more than once for risk stratification of cardiovascular system, such as SV, CO, SAC and TPR [6,10–12]. Nevertheless, in view of validity and reliability, it is still an arguable question for the left risk factors, including heart oxygen volume of consumption (HOV), pulmonary arterial pressure (PAP), and total blood volume (BV), etc. The evaluation of prototyping pulse waveform analyzer was based on both validated and hypothetic risk factors, as listed in Table 2. For each risk factor, there are a reference value (REF) derived from normal population, and the test result averaged from 7-day consecutive evaluations. It is noteworthy that, different from the reference value, there are three testing results for each subject because the participants had to accomplish 3 times of evaluations a day.

It is appropriate to claim the effectiveness of the prototyping pulse waveform analyzer from two aspects: in the first, the derived risk factors are consistent throughout the evaluation; in the second, those risk factors do exhibit distinction among various control cohorts. Coming to the results in Table 2, both variation and standard deviation of risk factors are less than 15% in multiple times of cardiovascular health monitoring. On the other hand, several critical risk factors, including SV, CO and BV, turn out to be distinguishable in terms of ages and health status of cardiovascular system. Take the participant "charley001" for example. His risk factors generally exceed those of control subjects in amount over 15%.

In contrast, the embedded medical advisory system does not always lead to sound health prognosis. Currently, that system is based on 64 pieces of diagnostic rules by medical experts. With those diagnostic rules, it is aimed to characterize the relationship between health status of cardiovascular system and

confidence intervals of various risk factors. However, it is yet an arguable question whether there are determinate solutions to medical inverse problems [28]. Take the subject "charley001" for example again. He has been confirmed with "premature ventricular contraction". But the embedded medical advisory system reported "normal cardiovascular system" more than once. It may be partially explained by the daily treatment of cardiovascular medicine. Nevertheless, from another point of view, it reflects the complexity of medical inverse problems too. Therefore, home subjects are advised to take the conclusions of that embedded medical advisory system for primary reference only.

5. Conclusion

In this paper, a mobile pulse waveform analyzer was proposed for cardiovascular health monitoring. In contrast to most commercial solutions, it is aimed to accomplish pulse waveform monitoring and analysis within a self-contained mobile platform. The prototyping system adopts a PVDF biosensor for pulse waveform acquisition, and carries pulse waveform processing and analysis with an ARM-based core board. Then, based on the derived risk factors, it takes advantage of an embedded medical advisory system for health prognosis. To facilitate manipulation, the prototyping system also equips a touch screen for graphic user interaction. A prospective validation has been undertaken to evaluate its maneuverability as well as effectiveness.

In a nutshell, the progressive achievements during the development of such mobile pulse waveform analyzer are beneficial to wearable apparatus for cardiovascular health monitoring at home. For example, the well-designed core board is compact but powerful enough for various complex tasks in physiological signal analysis. So our next research will be focused on system optimization from the aspects of biosensor and health prognosis.

A PVDF biosensor was employed for pulse waveform acquisition in the prototyping system. The biosensor accomplished filtering, amplification and others within a compact platform. Nevertheless, the ARM-based core board is surely able to undertake those preprocessing tasks. So it is appropriate to fully integrate that biosensor in stead of the extended serial communication. On the other hand, the current analyzer requires an additional step of blood pressure measurement for pulse waveform calibration. But such isolated procedure often incurs biased risk factors of pulse waveform analysis. Our research group is hereby working on a unified platform for blood pressure measurement and pulse waveform acquisition. The methodology discussed in [12] may serve as a good reference.

Coming to health prognosis, it has been observed that current embedded medical advisory system does not always lead to consistent health clues, which may be partially attributed to the insufficiency of medical rules. From another point of view, the inference mechanism based on confidence intervals is not enough to resolve complex medical inverse problems. In other words, it may be helpful to introduce more advanced technologies in soft computing, such as artificial neural networks, to the medical advisory system.

At last, it is noteworthy that current validation was within our research group only. Definitely, such prospective evaluation is not convincing enough to claim the validity and reliability of the mobile pulse waveform analyzer. Our research group is ready to recruit more volunteers with diversified demographic indices and health status of cardiovascular system. Then, its maneuverability and effectiveness could be further evaluated in virtue of those subjects without professional background.

Acknowledgments

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